FAST AND CRITICAL DETECTION DEVICES PLANNED FOR THE MACHINE PROTECTION SYSTEM AT THE FACILITY FOR RARE ISOTOPE BEAMS *

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Abstract

The Facility for Rare Isotope Beams (FRIB) at Michigan State University (MSU) will use a 400 kW, heavy-ion cw linac to produce rare isotopes in support of a rich program of fundamental research. In the event of operational failures, the Machine Protection System (MPS) shuts off the beam within microseconds to control beam losses that may damage accelerator components. The operational mode is distributed to all fast and critical devices that have multiple hardware checkpoints and comparators. A relational database provides the framework for the development of the MPS management application. In this paper, we present the FRIB MPS architecture, plans and implementation.

INTRODUCTION

MSU was chosen to design and establish FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics. The FRIB preliminary engineering design for the heavy-ion linac is well underway. The linac consists of a room temperature front-end system producing beams of approximately 0.3MeV per nucleon. Three additional superconducting linac segments produce beams of >200 MeV/u with a beam power of up to 400 kW. In the event of operational failures, the beam must be shut off promptly to control the beam losses that may damage accelerator components. FRIB has adopted the residual beam loss activation limit at 30 cm to be equivalent to 1W/m of uncontrolled operating beam losses to allow for hands-on maintenance.

MPS CONFIGURATION

MPS Requirements and Concept

The MPS must be a fast, reliable and robust system with the ability to turn off the beam within 35 to 45 µs (depending on fault location). The MPS has digital inputs from only the fast and/or critical devices. All other fault signals from devices that are not fast and/or critical are handled by the Beam Permit System.

This means that all MPS related devices must have information about the present mode of the machine, and they must interpret their status based on machine mode as well as their local inputs (smart devices). These smart devices provide a signal of OK or NOT OK (NOK) to the MPS. In the case of a NOK signal, the MPS turns off the beam by simultaneously commanding a 180° phase shift from the RFQ, activation of an electrostatic deflector, and by 100% duty cycle from the chopper. Furthermore, the MPS may slowly turn off the high voltage power supply to the ECR depending on the specific fault condition and machine mode. All devices must have the ability to lock their data buffers for post mortem analysis.

The initial status and all updates to inputs or outputs must be logged with timestamps. The MPS time must be synchronized with the Timing System and the MPS log is stored to a database.

The MPS must be flexible enough to accommodate commissioning, operations and future machine upgrades.

MPS Response Time

The MPS response time requirement is defined to be a maximum of 35 µs for faults occurring in linac segment 2, and 45 µs for faults occurring in all other segments of the linac and the beam delivery system. This time includes 15µs for the diagnostic device to detect and inform about the failure, 10 or 20 µs for the MPS to process the information and distribute the event to mitigation devices, and 2 µs to execute the mitigation action (*i.e.*, abort the beam). An additional 8 µs is provided to account for beam in the pipe.

The MPS processing time for each device does not increase with expansion of the system. However, as more MPS nodes are added, it may become necessary to extend the network with another layer of MPS switches. This adds another device with its processing time in the path between the detected fault and the mitigation output. Hence a powerful FPGA is needed to perform fast signal processing.

The MPS system uses a digital fiber optic network. The fiber propagation delay time depends on the length of the fiber cable (about 5 µs per 1 km). To minimize cable lengths, the MPS device location and network is carefully planned while also employing an effective protocol for data transmission. The time for a signal to pass from the input to the MPS device's internal logic (or vice versa for outputs) is negligible for a low number of I/O interfaces but may become significantly longer for a very large number of I/O interfaces per device thus requiring optimization of the number of I/O interfaces.

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MPS and Timing System

The Timing System (TS) is a dedicated hardware system that provides precise trigger information to diagnostics and enables data correlation. It also communicates with the MPS by checking on its "heartbeat" for an added layer of reliability. The timing system can broadcast globally useful events and data (e.g. mode switching and asynchronous events such as MPS beam abort). Since the MPS has a bi-directional optical communications interface to the TS, time stamps with a resolution of 100 ns can be achieved.

MPS and Control System

The FRIB Control System (CS) is EPICS-based [1]. The MPS has an interface to the CS to communicate information about its health, operational status and status of its interfaces, including all nodes and switches.

System Architecture

The two basic components of the MPS system are the MPS master and the MPS nodes. They are connected using a bidirectional optical switch in a tree topology network. Other topologies are also being considered. The MPS master serves as the entry point for integration with the CS and TS. It is also the central point of the MPS network.

The MPS master receives messages from all MPS nodes and is notified about detected faults on local devices. The protection logic is realized by fast and reliable FPGA processors with real-time communications interfaces. The MPS has a direct optical interface to the TS from which it can receive time synchronization and mode change messages. The TS can issue a mode change in run-time, which dynamically changes the behavior of the system using well defined response matrices.

The MPS master can perform mitigation actions based on fault messages by driving mitigation outputs or broadcasting messages for local mitigation actions. The MPS Master can also distribute response matrix configurations from the CS and timing information from the TS to other MPS devices through the MPS optical network. The CPU within the MPS Master has a built-in EPICS I/O controller that provides integration with the CS. Through this interface, response matrix configurations can be loaded into the MPS when the beam is off. When the beam is on, the CS can monitor MPS operation and device interfaces via status variables.

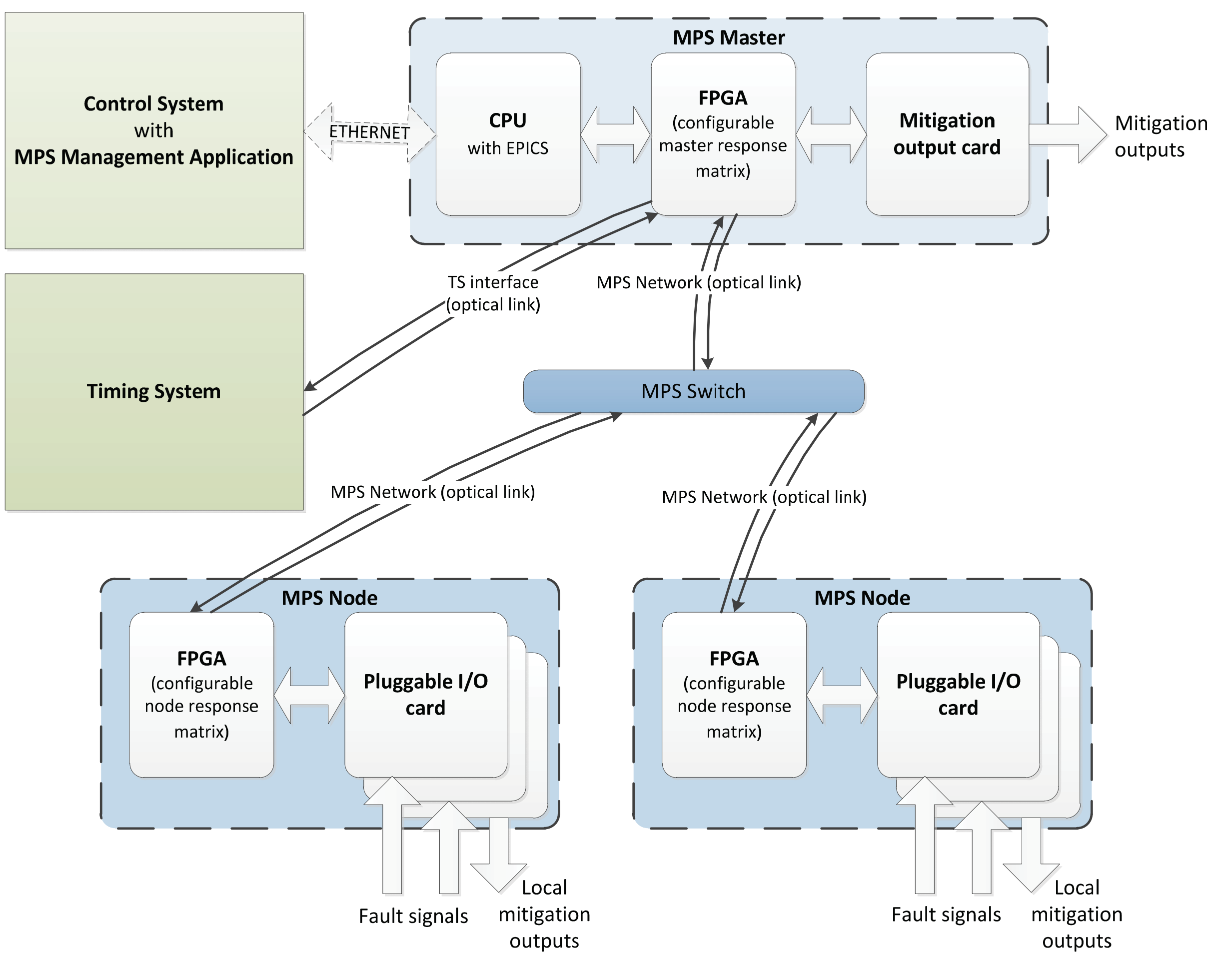

Figure 1: FRIB MPS System Architecture.

Similar to the MPS Master, MPS Node logic is implemented using FPGAs. The FPGA logic monitors the state of connected devices through pluggable input cards that can support different electrical interfaces. The input signals are conditioned internally where glitch rejection and similar functions can be performed. The MPS Node can also carry out local mitigation actions.

The FPGA processor also logs changes of inputs and outputs along with timestamps for post-mortem analysis. Logs from all MPS Nodes are time synchronized through events from MPS Master, which receives its timing information from the TS. When a mitigation action is performed, the logging is stopped and the internal logs are sent to the MPS Master through the MPS network.

The bidirectional MPS switch connects the MPS Nodes to one optical interface on the MPS Master. Messages from the MPS Nodes are received and buffered in the switch. A multiplexer takes out messages from the buffers according to priority and sends them to the MPS Master through a single upstream interface. The data transfer can be done in real-time, completely deterministically and with low jitter (about one tenth of the timestamp resolution). Time synchronization events are downstream messages from the master to nodes, that are broadcast without buffering and therefore delay and jitter are even smaller.

MPS Management Application (Software)

The MPS can be configured and monitored through the MPS management application. It consists of a standalone application or service within the CS. The MPS management application interfaces with a relational database (RDB) that serves as a global resource for the control system. The RDB provides three primary functions to the MPS: 1) manages configuration information, 2) stores machine mode masks required for operation, and 3) stores alerts, failures and device data buffers. All MPS inputs and outputs are associated with EPICS process variables. In addition, MPS node configuration parameters are mapped to process variables and stored in the database.

FAST AND CRITICAL DEVICES

Beam Loss Monitors (BLMs) and phase detectors are categorized as fast devices, while beam position monitors (BPMs), profile monitors (PMs) and other devices are categorized as critical devices. BLMs are the first to detect a serious problem with the beam. They ensure that the uncontrolled operating beam loss does not exceed 1 W/m. As smart devices, they evaluate their measurement based on their location and provide a binary signal (OK/NOK) to the MPS Master.

Each superconducting RF cavity is equipped with a phase detector that is connected to the low-level RF (LLRF) system. The LLRF then provides a signal to the MPS, indicating whether or not the phase is locked.

BPMs and PMs are considered to be critical devices because they provide essential information for post mortem analysis. They may trigger mitigation action under certain circumstances, but are typically too slow as faster devices such as BLMs will have already triggered mitigation action in the case of machine failure. Other inputs to the MPS are status signals from other critical systems such as the Personnel Protection System (PPS), Beam Permit System (BPS), cryogenic systems, magnets, etc.

MITIGATION DEVICES

The mitigation devices primarily consist of an electrostatic deflector that could be backed up by the chopper, the radio frequency quadrupole (RFQ) and the ECR. The location of the electrostatic deflector is chosen to minimize the residual beam deposition into the driver linac after the abort is pulled [2]. The chopper is located in the low energy section of the front end of the machine. When mitigation action is triggered, the MPS commands 100% chopping thus directing the beam to the Faraday cup (FC) within 2 µs. The FC provides a feedback signal to the MPS for verification that the beam is diverted from the beam line.

The RFQ is also located at the front end of the machine and facilitates the transition from the low to the medium energy section. For mitigation action, the MPS commands a 180° phase shift, which results in the elimination of particles being accelerated. This may take up to 20 µs. In addition, the MPS can turn off the ECR high voltage within milliseconds, thus preventing injection of charged particles.

CONCLUSIONS

The MPS for FRIB will meet the project requirements and adequately protect the machine. Critical system parameters, inputs, outputs, interfaces and integration with other systems have been defined within the scope of the preliminary engineering design.

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